E. Durability of Diesel Engine Component Materials

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Objectives

- Provide test data, analyses, and models that enable the use of durable, lower-friction moving parts in diesel engines in heavy vehicle propulsion systems.
- Develop test methods that simulate the environment of scuffing-prone engine parts.
- Conduct structural and tribological characterizations of promising new materials, surface treatments, composites, and coating technologies.

Approach

- Identify diesel engine components that need advanced materials or surface treatments in order to ensure durability while providing low-friction behavior. These include (a) wastegate bushings for exhaust gas recirculation (EGR) components and (b) fuel injector components.
- Identify materials, coatings, and/or surface treatments that have the potential to increase the durability of the selected engine components.
- Develop test methods to evaluate the performance of candidate materials under simulated use conditions.
- Develop graphical methods and models to portray the effects of operating parameters, like speed, load, and surface finish, on the scuffing response of the materials.

Accomplishments

- Designed, built, and used a high-temperature oscillatory scuffing test system that operates at wastegate bushing temperatures (~ 600–700°C).
- Published results of tests on a range of metallic alloys, ceramics, and coatings to determine which of these had the best durability under high-temperature conditions.
- Developed a novel, “pin-on-twin” scuffing test to evaluate fuel injector materials in diesel fuel and low-sulfur fuel.

- Developed criteria for the onset of scuffing damage and evaluated traditional steel fuel injector materials as well as ceramics, advanced cermets, and hard coatings in diesel fuel and low-sulfur fuel. Represented results in terms of "scuffing maps" and transition diagrams.
- Prepared a model for scuffing tendency that considers lubricant characteristics and solid material characteristics.

Future Direction

- Use scuffing damage maps and test data to support the development of the new scuffing model and to obtain a better understanding of the evolution of localized surface damage. Compare results of the model with laboratory test data on metals, ceramics, and composite materials.

Introduction

The diesel engine industry faces important challenges to improve fuel efficiency in the face of increasingly strict emissions regulations. These challenges can be addressed by modifying the engine design and electronic control systems for engines, and by developing exhaust gas after-treatments. Such modifications affect the mechanical, thermal, and chemical environments to which the engine materials are subjected; and the current structural materials may not perform as well as they did in previous designs.

The objective of this effort is to enable the selection and development of durable, lower-friction moving parts in diesel engines for heavy vehicle propulsion systems through the systematic evaluation of promising new materials, surface treatments, composites, and coating technologies. The current approach involves test method development, microstructural analysis of candidate materials, mapping the effects of applied parameters on surface damage, and modeling. The focus on EGR components and fuel injector plungers was based on discussions with diesel engine manufacturers. Before developing tests to evaluate materials for improved durability, however, it was necessary to conduct a tribosystem analysis to understand the conditions under which the surfaces of these components materials must perform in an operating diesel engine. The nature of contact damage to engine components was reviewed to ensure that laboratory test methods would adequately reproduce that kind of damage. Then the test development, data analysis, and modeling tasks were begun.

Approach

In FY 2001, based on the definition of several key durability problems, a test method was developed to study the high-temperature friction and wear characteristics of candidate EGR system materials. The testing system we built continues to be used to evaluate metal alloys, ceramics, coatings, and other experimental materials for that application. In FY 2002, this effort was extended to include an investigation of the scuffing of fuel injector component materials. Laboratory tests were developed and refined to produce and measure the type of fine-scale surface damage that is observed in diesel engine fuel system parts. In FY 2003, research continued in two areas: (1) evaluating the effects of diesel fuel sulfur reductions on scuffing and (2) identifying materials and coatings for high-temperature scuffing resistance in EGR components.

During FY 2004, a 3-dimensional (3D) scuffing map was developed to graphically depict conditions for scuffing initiation and propagation in time and space domains. It was applied to explore the effects of surface finish and sliding velocity on materials and coatings for fuel injector systems. Such scuffing maps are intended to aid designers to select more durable materials and to determine optimum surface finishes. Near the end of FY 2004, a new scuffing model was developed that integrates boundary film characteristics with material properties. Chemical analyses of scuffed surfaces were conducted to investigate the wear modes and tribochemical film compositions in a fuel-lubricated environment, underpinning the basis for the model. Plans for FY 2005 involve refining and improving the model using experimental data concerning the friction and surface damage of advanced materials for durable diesel engine components.

Results

As reported previously, a pin-on-twin pins test was developed to evaluate the scuffing tendencies of diesel fuel injector plunger materials in commercial diesel fuel and in a low-sulfur fuel. That test was used to rank a variety of promising new materials such as cermets and ceramics. Data were in the form of exposure time prior to the onset of scuffing. In considering the data, it was quite clear that many different variables could affect scuffing, and there was a need for a better method to display the data for visualizing combinations of variables. Therefore, work in FY 2004 involved studying the current data and developing a format to display it.

After the relevant issues were considered, a 3D friction-scuffing mapping technique was developed to present surface damage progression in the space and time domains. The concept is based on the assumption that an increase of the friction force at a certain location corresponds to lubricant film breakdown and surface morphology changes at that location. Scuffing is associated with asperity-level or grosser surface changes, such as plastic deformation and material displacement. Therefore, we might expect the rise in the plowing contribution of the friction force to reflect an increased incidence of surface deformation and hence become an indicator of scuffing. This correlation was verified by optical surface morphology examinations and electron microscopy.

An example of a 3D friction-based scuffing map is provided in Figure 1. The change of friction coefficient relative to that of the first stroke in the test is portrayed as the vertical axis in Figure 1. One horizontal axis represents the location along the length of the stroke, and the orthogonal axis represents the cumulative time of sliding contact. Shaded horizontal bands, defined in the Figure 1 legend, represent ranges of friction coefficient. The test used to construct Figure 1 used a reciprocating pin-on-twin pins configuration and was conducted on self-mated AISI 52100 steel in ultra-low-sulfur fuel (Jet A aviation fuel). By defining a threshold change in friction coefficient to signal the initiation of scuffing (e.g., an increase of 10% over the initial friction coefficient), it is possible to use the friction-scuffing map to indicate the location and progress of scuffing damage.

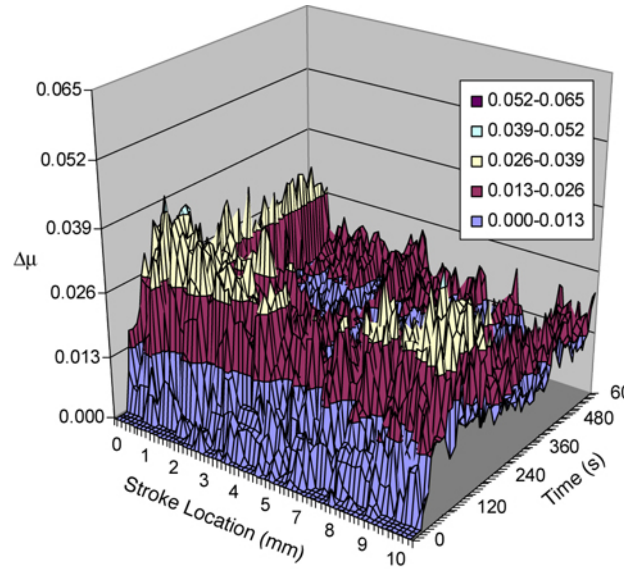

Figure 1. A 3D friction-scuffing map for self-mated bearing steel is plotted in space and time domains.

Three-dimensional friction-scuffing maps like that in Figure 1 were subsequently used to construct scuffing transition diagrams to portray the effects of surface roughness and sliding velocity on scuffing resistance for diesel fuel injector materials, such as AISI 52100 steel and transformation-toughened zirconia (TTZ).

Figure 2 depicts the time until the first instance of scuffing for specimens with different initial surface roughness in ultra-low-sulfur fuel. Scuffing usually initiates locally, generally at the ends of the stroke; and surface damage may or may not spread along the whole sliding stroke during the course of the test. In Figure 2, the ‘local scuffing’ curve refers to the moment of the onset of local scuffing, and the ‘global scuffing’ curve implies when the whole stroke was scuffed. The region between these two curves represents the period of scuffing propagation from local spots to the whole stroke. This outside-inward spreading is a consequence of the sliding motion. The velocity of our pin-on-twin reciprocating test follows a sinusoidal wave form. The sliding speed starts at 0 at the turnaround points and reaches a maximum at the stroke’s midpoint. Scuffing, if it occurred, generally appeared at the stroke ends first, because there is less effective lubrication there and the lack of lubrication leads to more solid-to-solid contact.

Compared with self-mated steel, zirconia against steel performed better at each surface finish

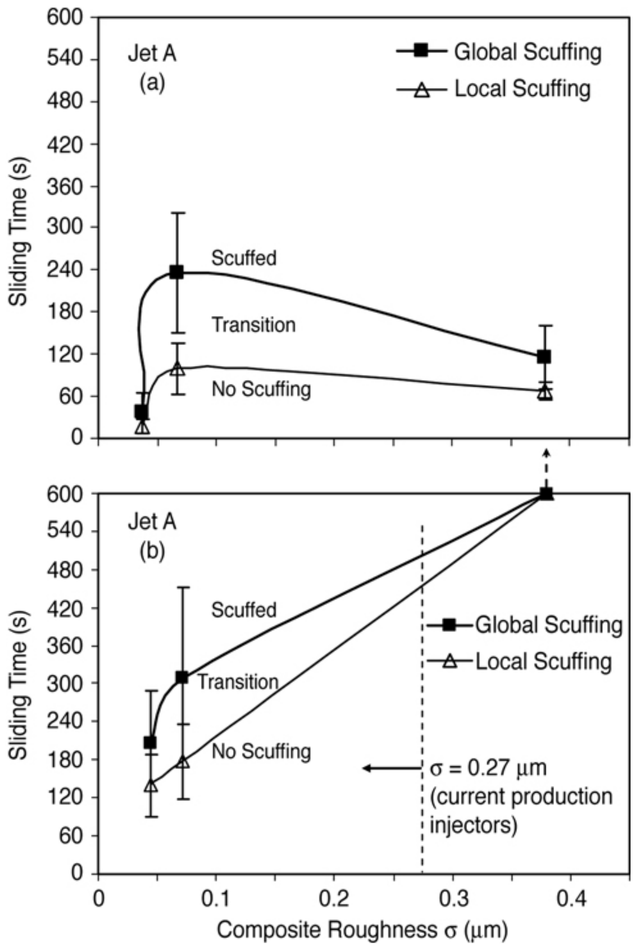

Figure 2. Scuffing transition diagrams for 52100 steel and TTZ in ultra-low-sulfur fuel.

level. Smoother contact surfaces tend to produce thinner lubricant films and more chance for incidental contact, but rougher surfaces have higher local contact pressure under boundary lubrication conditions. Either case may cause the lubricant to fail. Therefore, there is likely to be an optimum surface finish to provide the best scuffing resistance for a given lubricated sliding system. The steel specimens with intermediate roughness outperformed other two surface finish levels (Figure 2a), while rougher surfaces showed higher scuffing resistance for TTZ against steel (Figure 2b). The composite roughness* of the current-production zirconia plunger and 52100 steel bore in heavy-duty diesel engines is about 0.27 μm. To meet stricter diesel engine emissions standards, superior surface finish and tighter tolerances are required to seal the higher injection pressures. Better surface finish would reduce the scuffing resistance of the injector system, according to the scuffing transition diagrams in Figure 2b. This necessitates the investigation of new materials or surface engineering processes to resist scuffing under the more stringent operating conditions.

Under boundary lubrication, tribochemical films formed on contact surfaces play an important role in scuffing behavior. Depending on the specifics of the tribosystem, these in-situ formed films can be either protective or detrimental.[1] In the current investigation, the surface films formed in our fuel-lubricated scuffing tests have been examined and analyzed using optical microscopy, scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), and scanning auger microprobe (SAM).

For zirconia/steel pairs with relatively smooth surfaces, a tribo-film could easily be observed under a light optical microscope on both sides of the contact surfaces after scuffing. The brown or dark-reddish color suggested the presence of iron oxides such as FeO and/or Fe_2O_3. EDS analysis confirmed that oxygen was present in this layer. The scuffing process of zirconia against steel seemed to be a competition between the formation and removal of this tribochemical film. Although the oxide layer may protect the original surfaces from abrasive wear to some extent, its non-uniformity and the resulting adhesion and spallation problems make it undesirable for fuel-injection systems with very tight geometric clearances.

To better understand the scuffing transition in fuel-lubricated systems, the tribochemical surface films at an early scuffing stage were analyzed using a PHI 680 SAM. Figure 3 shows the sputtering depth profiles of elemental compositions for the surface films on and off the wear scar on a bottom steel pin (against steel) in Jet A fuel. There was a relatively thick (about 80 nm) iron-oxide-rich layer on the worn surface, compared with that (< 4 nm) on the unworn surface. This demonstrated that tribochemical excitation, such as frictional heating and mechanical deformation, significantly accelerated the oxidation process.[2] The surface film formed in #2 diesel fuel showed a thinner oxide-rich layer with lower oxygen concentration than the film formed in Jet A fuel. This implied that the diesel fuel "cooled"

* Composite roughness is defined as the square root of the sum of the squares of the arithmetic average surface roughnesses of both mating surfaces.

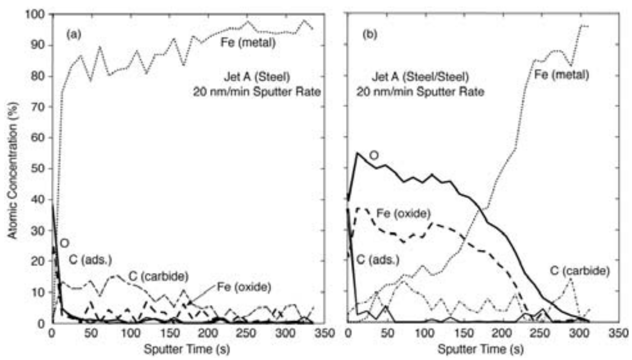

Figure 3. SAM sputtering profiles of surface films that were formed during tests in ultra-low-sulfur fuel.

the contact area more effectively, which probably helped to resist scuffing. The diesel-fuel-lubricated surface also had a higher non-carbide carbon concentration, which suggested that possibly more polymeric materials or organometallic compounds, thought to be generally protective, were deposited on the contact surfaces. These observations helped to explain the higher scuffing resistance in #2 diesel fuel than in Jet A fuel.

In late FY 2004, a new model for scuffing was developed. It was based on the recognition that a sequence of interfacial events needs to occur to set the stage for scuffing. First, the lubricant film must cease to effectively protect and separate the surfaces; next, the solids in contact must begin to accumulate damage to the point that significant deformation, roughening, and elevated friction occur. These phenomena have been embodied in a model for scuffing that was described in a project milestone report (see publications list) and will be further evaluated and refined in the light of additional experiments to be done in FY 2005.

Conclusions

- 3D friction-scuffing maps have been developed to depict scuffing initiation in both time and space domains. These maps were used to construct scuffing transition diagrams that correlate scuffing resistance to surface finish and sliding velocity.
- In the range of surface roughness tested in this study, zirconia against steel showed the scuffing resistance to be proportional to the composite surface roughness, while self-mated steel exhibited optimum performance with an intermediate surface finish.
- A thinner oxide layer and a higher non-carbide associated carbon concentration were detected on the #2 diesel-fuel-lubricated surfaces. This implied lower temperature and more protective organometallic compounds formed on the contact area. These observations could partially explain the higher scuffing resistance in normal diesel fuel than in ultra-low-sulfur fuel
- A combination of experimental data, surface observations, and derived scuffing transition diagrams led to the development of a new scuffing model. This model will be tested and validated in the year to come.

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